Communications Network Economics

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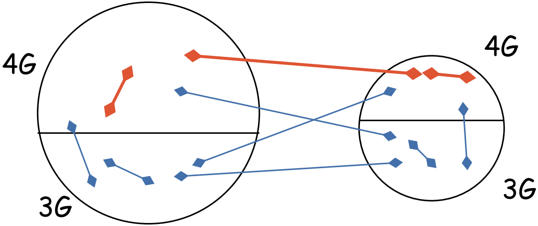
March 2017

The Role of Economics in Networking

1. Explain operator behaviors
2. Predict network equilibrium
3. Envision network services
4. Provide policy recommendations

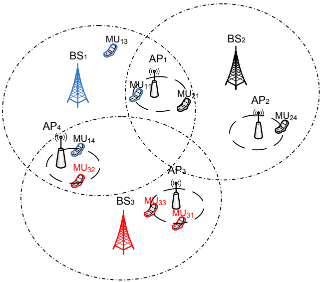
Explain Operator Behaviors



- Operators of similar sizes upgrade technologies at different times
- A tradeoff between market share and upgrading cost
- Network effect provides additional benefit to late upgrade

[Duan-**H**-Walrand] "Economic Analysis of 4G Network Upgrade," *IEEE Transactions on Mobile Computing*, May 2015

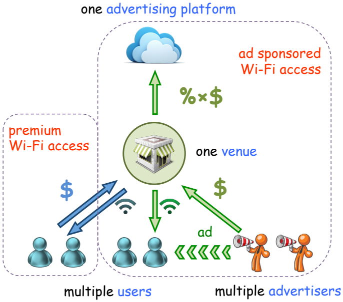
Predict Network Equilibrium



- On-demand data offloading from cellular networks to Wi-Fi networks
- When, where, and how much to offload?
- Market clearing through an iterative double auction mechanism

[Iosifidis-Gao-**H**-Tassiulas] "An Iterative Double Auction for Mobile Data Offloading" *IEEE/ACM Transactions on Networking*, October 2015 (*IEEE WiOpt* 2013 Best Paper Award)

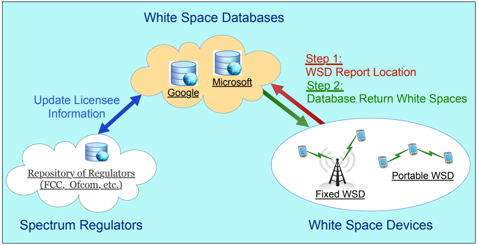
Envision Network Services



- Monetization of the public Wi-Fi networks
- Free ad-sponsored Wi-Fi access vs. premium paid Wi-Fi access
- Optimal pricing mechanisms based on user valuation, visiting frequency, and advertisement concentration

[Yu-Cheung-Gao-**H**] "Public Wi-Fi Monetization via Advertising," *IEEE/ACM Transactions on Networking*, forthcoming (*IEEE INFOCOM* 2016 Best Paper Award Finalist)

Provide Policy Recommendations



- TV white space as golden unlicensed spectrum resources
- White space database operator manages the interferences
- Information market provides differentiated service to users

[Luo-Gao-**H**] "MINE GOLD to Deliver Green Communication in Cognitive Communications," *IEEE Journal on Selected Areas in Communications*, December 2015 (*IEEE WiOpt* 2014 Best Paper Award)

Media Coverage


Features
Making the Most of White Space


COMMUNICATIONS AND PUBLIC RELATIONS OFFICE
Press Releases


中大「Super Wi-Fi」新模型「平靚正」

中大學者研超級Wi-Fi優化接收

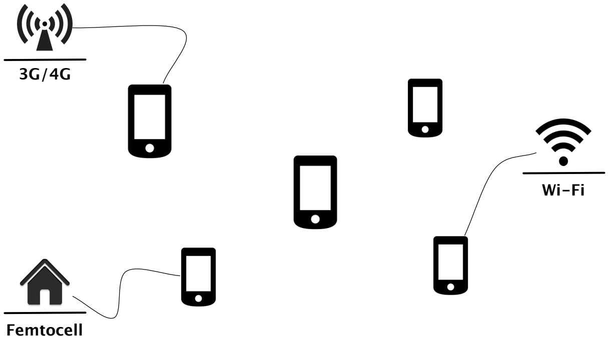
- Coverage by CUHK and in 20+ Hong Kong and Mainland Chinese news agencies (e.g., Mingpo, Sina, Sohu, and ChinaDaily)

Economics of User-Provided Networks

Joint work with Ming Tang & Lin Gao (CUHK)

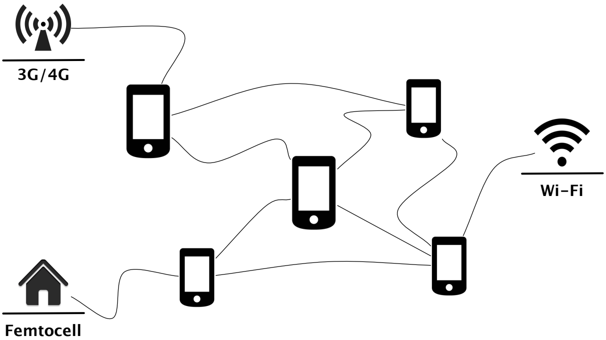
Haitian Pang & Shou Wang & Lifeng Sun (Tsinghua University)

Infrastructure-Based Network



- A user obtains network connectivity from a network provider
- No network connectivity outside the network coverage
- Clear distinction between "providers" and "users"

User-Provided Network



- Users serve as micro-providers, offering connectivity to other users
- Exploit the diversity of user devices
- Extend coverage and service of network operators
- Better match demand and supply in heterogeneous networks

Commercial UPNs

	Fixed Hosts	Mobile Hosts
Network-Assisted	Fon	Karma
Autonomous	BeWiFi	Open Garden

Costs and Incentives

- Resource sharing induces costs:
  - Reduced internet access bandwidth
  - Increased data usage cost
  - Reduced battery energy (for mobile users)
- Proper incentive mechanisms are critical for the success of UPNs

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  - Reduced internet access bandwidth
  - Increased data usage cost
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- Proper incentive mechanisms are critical for the success of UPNs
- We will focus on the incentive mechanism design for UPN-based mobile video streaming.

Single-User Video Streaming

My downloading speed is 0.5Mbps, want to watch video.

A

I can watch 240p in YouTube Live, with the downloading speed of 0.5Mbps.

My downloading speed is 1Mbps, do not watch video.

B

My resource is idle.

Multi-User Cooperative Video Streaming

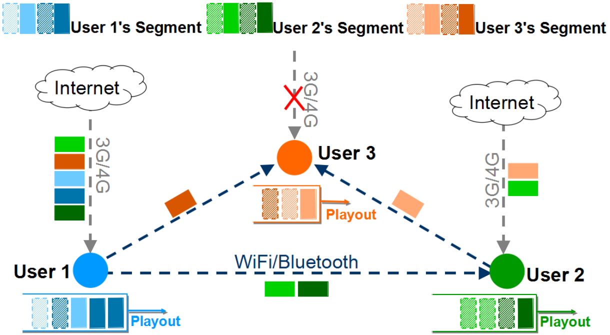
My downloading speed is 0.5Mbps, want to watch video.

My downloading speed is 1Mbps, do not watch video.

I can watch 720p in YouTube Live, with the downloading speed of 1.5Mbps.

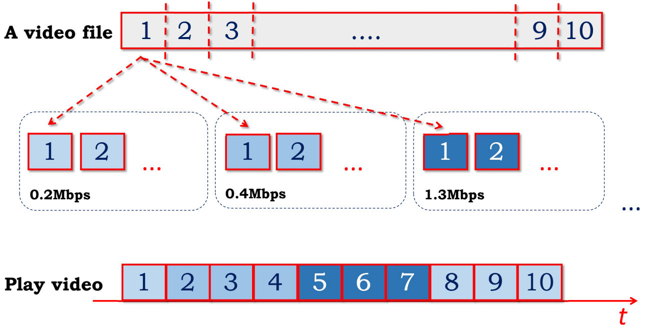
Resource is utilized, any reward for me?

Crowdsourced Mobile Video Streaming



- Crowdsource network resources from multiple near-by mobile users from potentially different service providers.
- Each mobile user watches a different video.

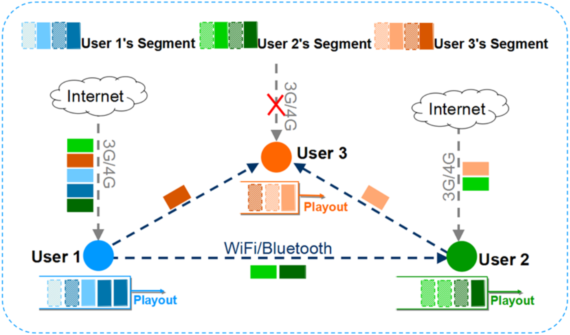
Adaptive BitRate Streaming



- To achieve flexible Quality of Experience in wireless video streaming
- Single user case: choose the bitrate of each video segment based on real-time network conditions and user QoE preferences.

Multi-User Collaborative Video Streaming

- Three decisions when downloading a video segment



Receiver Selection:
Whose segment ?

Bitrate Adaptation
What bitrate ?

Cost Compensation
How much to pay ?

Multi-User Collaborative Video Streaming

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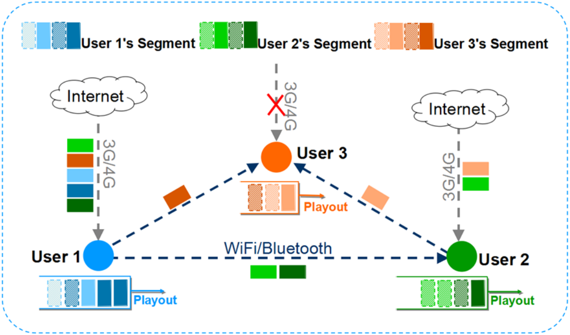

Receiver Selection: Whose segment ?

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Cost Compensation How much to pay ?

- Need decentralized and asynchronous algorithm without complete network information

Social Welfare, Utility, and Cost

- User n downloads a segment of bitrate r for user m at time t_0

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- Utility of receiver user m

$$U_m(r) \triangleq \underbrace{\log(1+\theta_m r)}_{video\ \ quality} - \underbrace{\phi^{\mathrm{QD}}\left[R_m^{\mathrm{PRE}} - r\right]^+}_{quality\ \ degradation\ \ loss} - \underbrace{\phi^{\mathrm{REB}}\left[T_n(r,t_0) - B_m^{\mathrm{CUR}}\right]^+}_{rebuffering\ \ loss}$$

  - (Private) valuation information θ_m
  - (Private) state information $\boldsymbol{\mu} = (R_m^{\mathrm{PRE}}, B_m^{\mathrm{CUR}})$

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  - (Private) valuation information θ_m
  - (Private) state information $\boldsymbol{\mu} = (R_m^{\mathrm{PRE}}, B_m^{\mathrm{CUR}})$

- Cost of downloader user n

$$C_n(r) \triangleq \underbrace{G_n^{\mathrm{CELL}}(r)}_{cellular\ \ data\ \ payment} + \underbrace{E_n^{\mathrm{CELL}}(r)}_{cellular\ \ energy} + \underbrace{E_{nm}^{\mathrm{WIFI}}(r)}_{WiFi\ \ energy}$$

Design Objectives

- Truthfulness: users truthfully reveal their utility functions despite of private information
- Efficiency: design a resource allocation mechanism to maximize the social welfare
- Optimality: design a resource allocation mechanism to maximize the downloader's benefit

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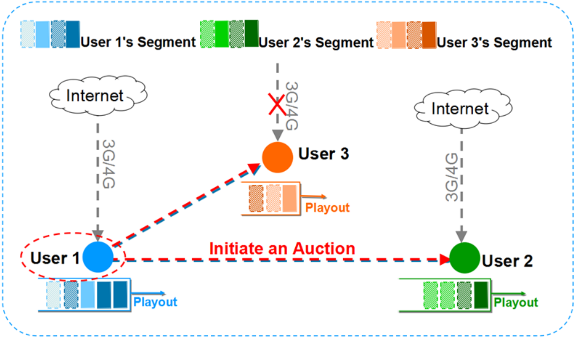
- Efficiency and optimality are conflicting objectives.
- We will focus on achieving truthfulness and efficiency through a multi-dimensional auction mechanism

Auction-Based Incentive Mechanism



User 1
(Ready to download)
Initiate an auction

User 1, 2, 3
Submit bid with (bitrate, price)
-Bitrate Adaptation

User 1
Winner & Payment
-Receiver Selection
-Cost Compensation

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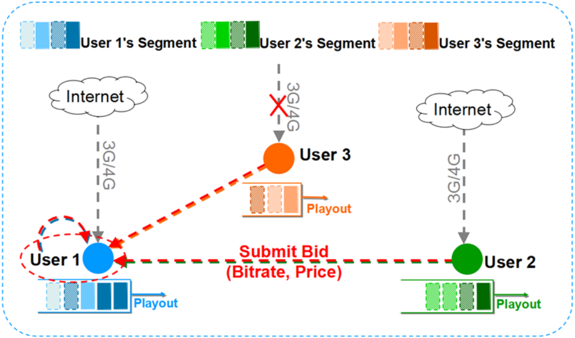

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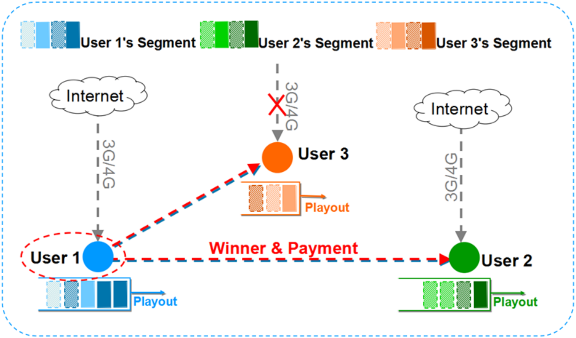

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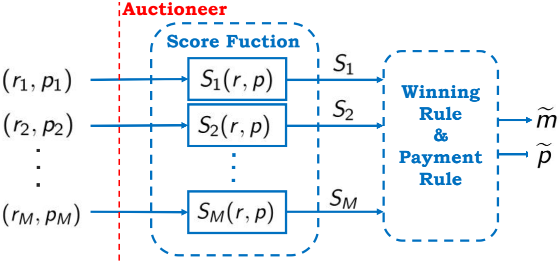
Challenge: Multi-Dimensional Bids

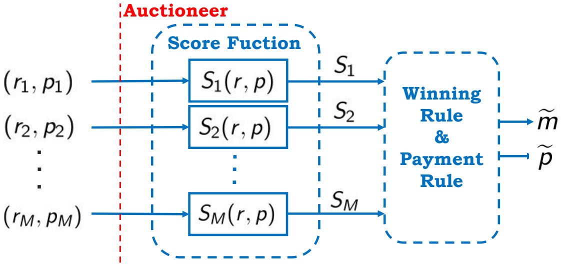
- Each bid is multi-dimensional: (bitrate, price)
  - (0.2Mbps, 20¢) vs. (0.4Mbps, 35¢) vs. (1.3Mbps, 70¢)
- How to rank vectors to decide the winner and the payment?
- Solution: Second Score Auction

Score Function



- Score function: transforms a multi-dimensional bid to a scalar
  - Determined by the auctioneer (mechanism design)
  - Each user m can have a unique score function $S_m(r, p)$

Score Function



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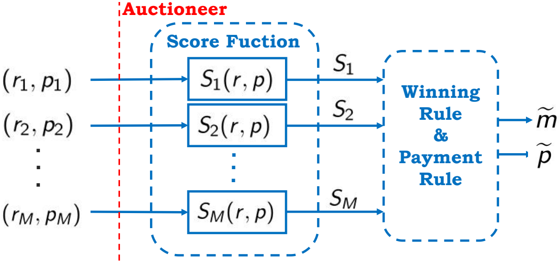

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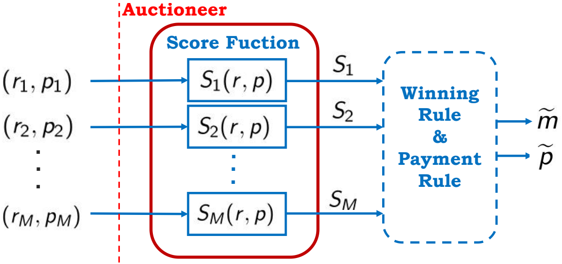
- How to choose the score function?

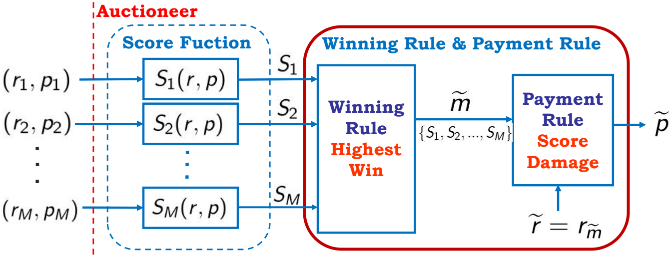
Additive Score Function



$$S_m(r,p) = p - C_n(r)$$

- Difference between the bidder m's price and the downloader n's cost
- All bidders have the same score function (related to downloader n)

Winner Selection and Payment Determination



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$$m^* = \arg\max_{m \in \mathcal{N}_n} (p_m - C_n(r_m))$$

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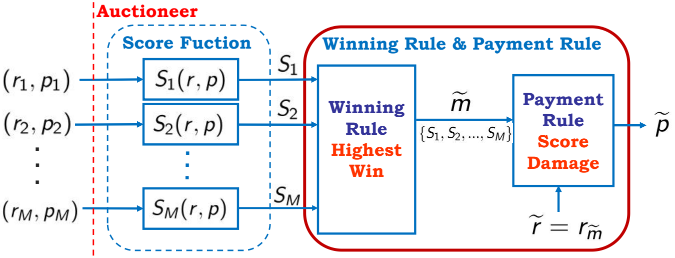

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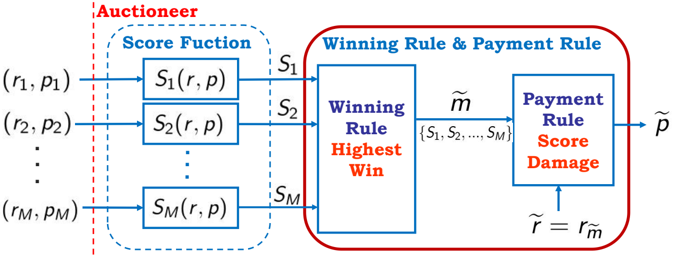

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- Winner's **bitrate** = the winner's bid bitrate r_{m^*}
- Winner's **payment** $\neq$ the winner's bid price p_{m^*}
  - Payment $\hat{p}_{m^*}$ represents the score damage to other users

$$\underbrace{\hat{p}_{m^*} - C_n(r_{m^*})}_{winner's\ \ revised\ \ score} = \underbrace{\max_{m \in \mathcal{N}_n / m^*} S_m(r_m, p_m)}_{second\ \ highest\ \ bidding\ \ score}$$

An Example

- A total of 3 bidders, and the score function is

$$S(r,p) = p - C_n(r) = p - 50 \cdot r$$

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$$\begin{aligned} S(r_A, p_A) &= 20 - 50 \cdot 0.2 &= 10 \\ S(r_B, p_B) &= 35 - 50 \cdot 0.4 &= 15 \\ S(r_C, p_C) &= 70 - 50 \cdot 1.3 &= 5 \end{aligned}$$

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- Hence B is the winner, and the bitrate is 0.4Mbps.
- The payment of B is $\hat{p}_B$:

$$\hat{p}_B - C_n(r_B) = \hat{p}_B - 50 \cdot 0.4 = \max_{m \in \mathcal{N}_n / B} S(r_m, p_m) = 10$$

$$\Rightarrow \hat{p}_B = 30¢.$$

Equilibrium User Bidding Behavior

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Theorem (Truthful Price Choice)

Given any bitrate r, a bidder m's equilibrium bidding price p_m is his true utility under r:

$$p_m(r) = U_m(r).$$

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Theorem (Bitrate Selection)

A bidder m's equilibrium bitrate r_m maximizes its score function, which corresponds to the social welfare if downloading for bidder m:

$$r_m = \arg\max_r \left(U_m(r) - C_n(r)\right) = \arg\max_r W_{nm}(r).$$

Efficiency

Theorem (Efficient Auction)

Under the following score function

$$S_m(r, p) = p - C_n(r),$$

the auction is efficient as it maximizes the social welfare.

Multi-Object Multi-Dimensional (MOMD) Auction

- One auction per segment may induce high signaling overhead
- How about allocating multiple objects (segments) per auction?
- Same design objectives: truthfulness and efficiency.
- A challenging problem in multi-dimensional auction.

MOMD Auction: Bidding

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  - bitrate matrix

$$\boldsymbol{R}^m = \begin{bmatrix} \boldsymbol{r}_1^m \\ \boldsymbol{r}_2^m \\ \vdots \\ \boldsymbol{r}_K^m \end{bmatrix} = \begin{bmatrix} r_{11}^m & 0 & \dots & 0 \\ r_{21}^m & r_{22}^m & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ r_{K1}^m & r_{K2}^m & \dots & r_{KK}^m \end{bmatrix}$$

★ r_{li}^m: the bitrate for the i^{th} segment if bidder m is allocated l segments.

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    - ★ r_{li}^m: the bitrate for the i^{th} segment if bidder m is allocated l segments.
  - price vector

$$\boldsymbol{p}^m = (p_1^m, p_2^m, ..., p_K^m)$$

    - ★ p_l^m: the total price if bidder m is allocated l segments.

An Example

- An auction allocates $K = 4$ segments.
- User m's bid: $(\boldsymbol{R}^m, \boldsymbol{p}^m)$
  - bitrate matrix

$$\boldsymbol{R}^m = \begin{bmatrix} \boldsymbol{r}_1^m \\ \boldsymbol{r}_2^m \\ \boldsymbol{r}_3^m \\ \boldsymbol{r}_4^m \end{bmatrix} = \begin{bmatrix} 1.3\text{Mbps} & 0 & 0 & 0 \\ 0.4\text{Mbps} & 1.3\text{Mbps} & 0 & 0 \\ 0.4\text{Mbps} & 0.4\text{Mbps} & 0.4\text{Mbps} & 0 \\ 0.2\text{Mbps} & 0.2\text{Mbps} & 0.2\text{Mbps} & 0.4\text{Mbps} \end{bmatrix}$$

    - ★ Different segments can have different bitrates (e.g., 2nd row)
    - ★ As the number of segment allocation changes, the bitrates of the same segment can change (e.g., 3rd column)
  - price vector

$$\boldsymbol{p}^m = (70¢, 105¢, 120¢, 135¢)$$

MOMD Auction: Score Function

- Score function if bidder m is allocated l segments:

$$\phi(\boldsymbol{r}_l^m, p_l^m) = p_l^m - C_n(\boldsymbol{r}_l^m), \forall l \in \{1, \ldots, K\}$$

  - $\boldsymbol{r}_l^m$ is lth row of bidder m's bidding matrix.

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- Compute the marginal scores:

$$\boldsymbol{S}^m = \{S_1^m, S_2^m, ...S_K^m\},$$

where

$$S_k^m = \begin{cases} \phi(\boldsymbol{r}_1^m, p_1^m), & l = 1 \\ \phi(\boldsymbol{r}_l^m, p_l^m) - \phi(\boldsymbol{r}_{l-1}^m, p_{l-1}^m), & l \geq 2 \end{cases}$$

  - Score increase due to each additional segment allocation

MOMD Auction: Winner & Payment

- Winners: the bidders that submit the highest marginal scores
    - Can have multiple different winners
- Payment: the marginal score damage that caused by the winner

An Example

- A total of 3 bidders, and an auction allocates $K = 4$ segments.
- The marginal score $\boldsymbol{S}^m$ for three bidders:

$$\boldsymbol{S}^1: \ \{8, \ 7, \ 5, \ 2\};$$
$$\boldsymbol{S}^2: \ \{9, \ 6, \ 3, \ 2\};$$
$$\boldsymbol{S}^3: \ \{4, \ 4, \ 3, \ 1\}.$$

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- Winners based on the highest 4 marginal scores $\boldsymbol{S}^\dagger = \{9, 8, 7, 6\}$
  - User 1 wins two segments, and user 2 wins two segments

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- Winners based on the highest 4 marginal scores $\boldsymbol{S}^{\dagger} = \{9,\ 8,\ 7,\ 6\}$
  - User 1 wins two segments, and user 2 wins two segments
- Payment of user 1 based on marginal score damage
  - Without user 1, the highest 4 marginal scores are $\hat{\boldsymbol{S}}^{-1} = \{9,\ 6,\ 4,\ 4\}$
  - Due to user 1, user 3 loses two segments with marginal scores $\{4, 4\}$
  - User 1's payment $\widetilde{p}_1$ needs to compensate his marginal core damage

$$\underbrace{\widetilde{p}_1 - C_n(\boldsymbol{r}_2^1)}_{score\ \ function} = \underbrace{4 + 4}_{score\ \ damage}$$

MOMD Auction: Properties

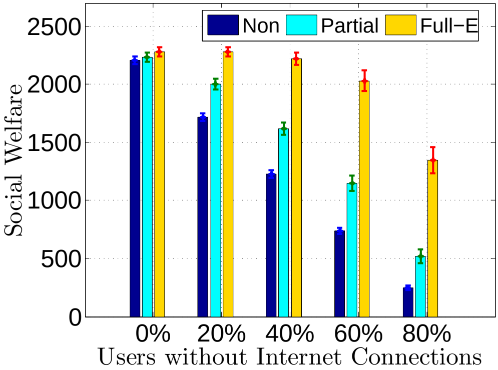
Theorem (Truthfulness and Efficiency)

Under a mild technical condition, we can prove the truthfulness of the users' bidding at the equilibrium, and show that the auction is efficient.

Simulation

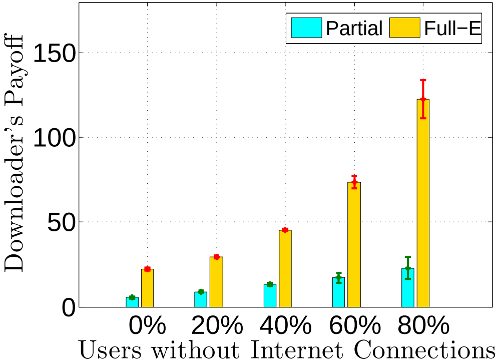
- 50 video users
- Link capacities derived from real traces
- 3 schemes for single-object multi-dimensional auction
  - Non: Non-cooperative benchmark
  - Partial: Partially cooperative benchmark (in pairs)
  - Full-E: Fully cooperative with efficient score function

Social Welfare



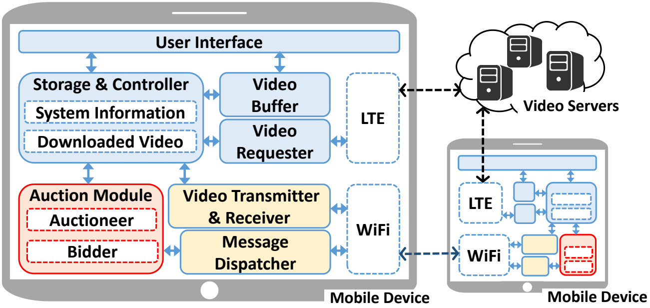
- Social welfare decreases with the disconnected use percentage
- When 80% of users do not have Internet connection, full cooperation is 5 times better than non-cooperation.

Downloader's Payoff



- Downloader's payoff increases with disconnected user percentage
- When 80% of users are disconnected, full cooperation is 5 times better than partial cooperation.

Demonstration System



- Mobile devices: Raspberry PIs, with monitors, LTE USB modems, and Wi-Fi adapters.
- Devices can dynamically join and leave the cooperative group in a decentralized fashion.

Future Work

- Mobility management
- Impact of social relationship
- Trust and security

The Big Picture

- New paradigm of network sharing
  - Blurring the boundaries among networks
  - New perspectives on network competition and cooperation
  - New pricing plans and economic mechanisms
- The rise of collaborative economy in communication networks
  - Business-to-Business (B2B) collaborations
  - Business-to-Consumer (B2C) collaborations
  - Peer-to-Peer (P2P) collaborations
- The need of data-driven network economics
  - Data analytics lead to new opportunities for technology improvement and economic mechanism design


THANK
YOU